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A Two-Stage Multi-Criteria Decision for Distributed Wind and Solar Integration

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A Two-Stage Multi-Criteria Decision for Distributed Wind and Solar Integration

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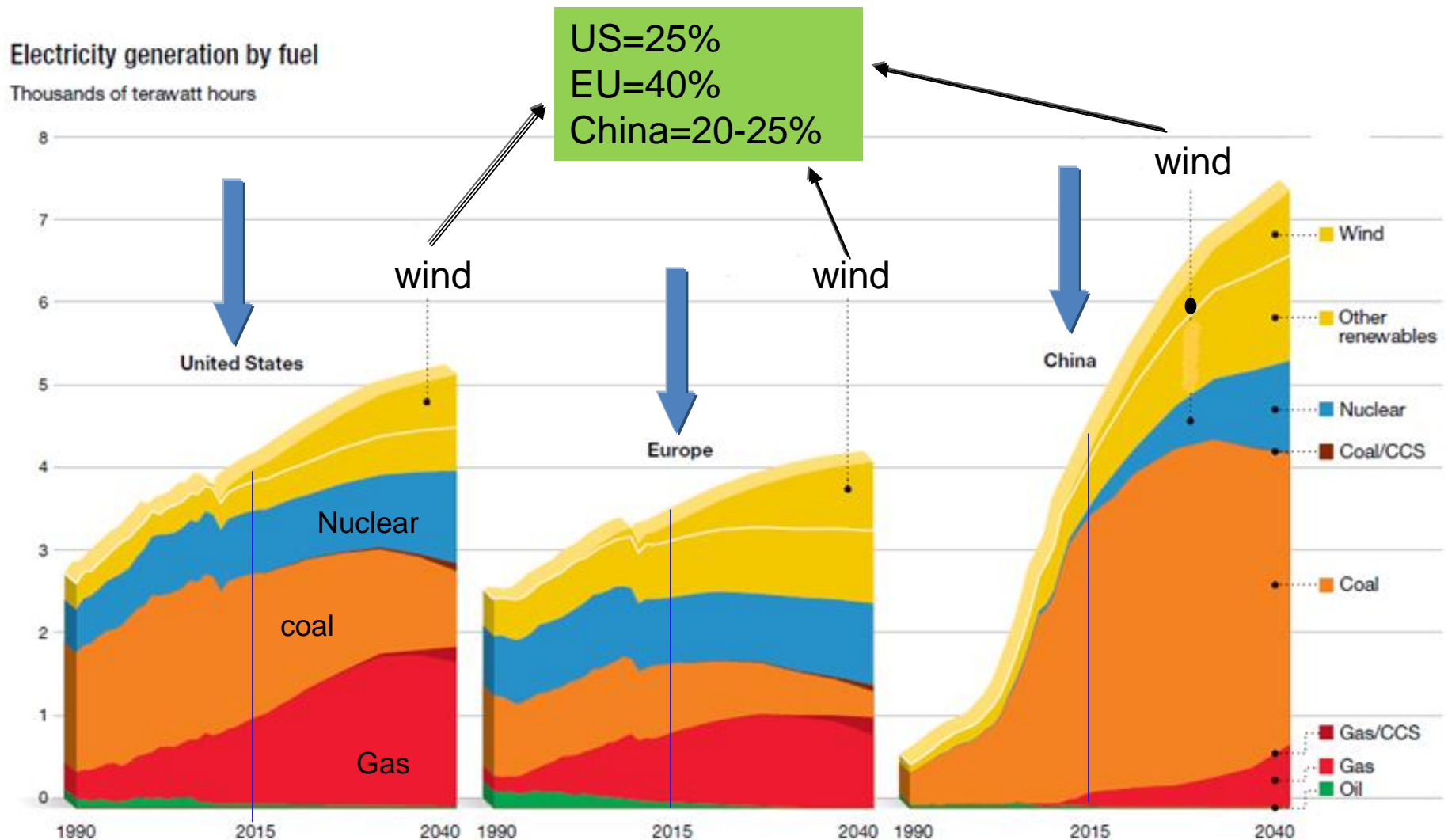
Glasgow Caledonian University, UK

Outline

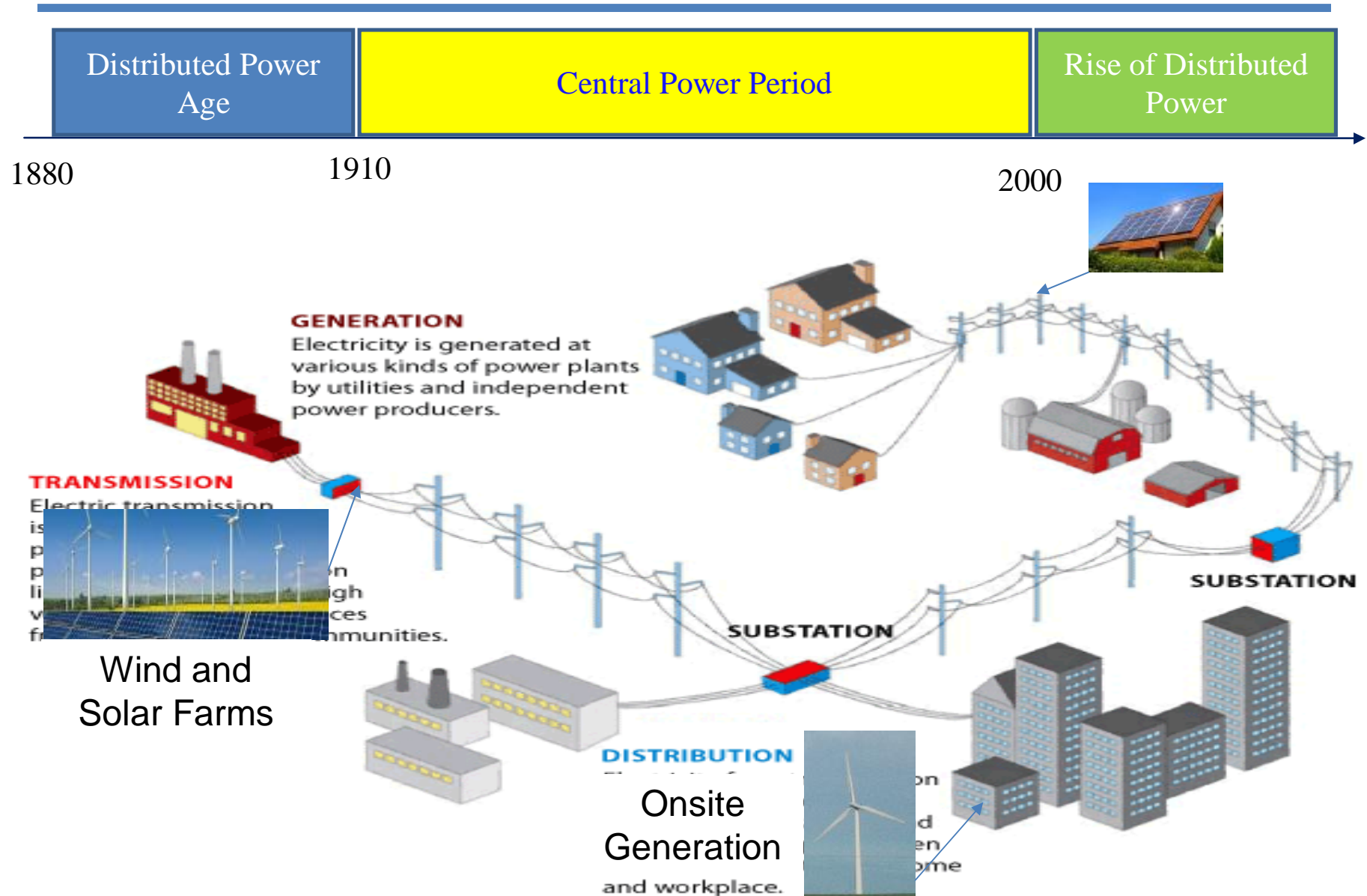
- I Toward Distributed Generation
- I Characterizing Wind and Solar Generation
- I Multi-Criteria Planning Model
- I Numerical Experiment
- I Conclusion

Renewable Portfolio Standards in 2040

3



The Rise of Distributed Power Service



Wind power in Scotland

Wind power is Scotland's **fastest** growing renewable energy technology, with 2574 MW of installed capacity as of April 2011. For example:

Whitelee Wind Farm is the **largest** on-shore wind farm in the United Kingdom with 215 Siemens and Alstom wind turbines and a total capacity of **539** MW.

The Clyde Wind Farm is a **350** MW on-shore wind farm near Abington in South Lanarkshire, Scotland.

The Robin Rigg Wind Farm is a **180** MW development completed in April 2010, is an off-shore wind farm sited on a sandbank in the Solway Firth.

Wind power in Scotland

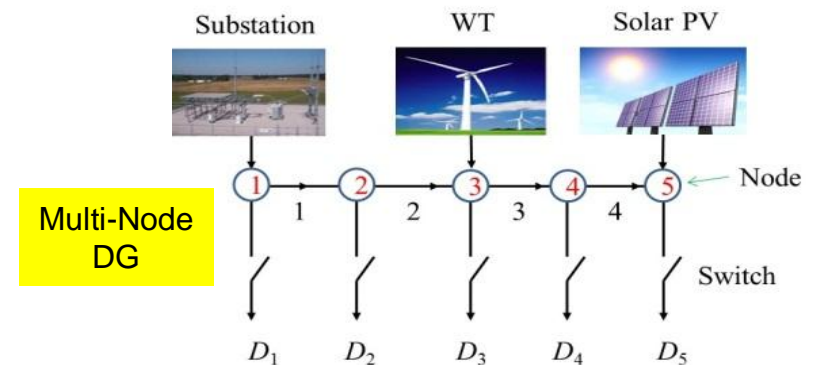
Large wind farms in Scotland:

- | Black Law Wind Farm
- | Braes of Doune Wind Farm
- | Clyde Wind Farm
- | Crystal Rig Wind Farm
- | Farr Wind Farm
- | Hadyard Hill Wind Farm
- | Robin Rigg Wind Farm
- | Whitelee Wind Farm

There is **further potential** for **expansion**, especially offshore given the high average wind speeds, and a number of large offshore wind farms are **planned**.

Type of Distributed Generation (DG)

- 1) Generation backup
- 2) Onsite generation
- 3) Multi-node Generation
- 4) Microgrid System



A commercial micro-grid system in China

Location: Turpan, Xinjiang

Year: 2009

Capacity: 13.4 MW PV

Service: 7,000 homes

Funded: Energy Foundation China's Renewable Energy Program

Key Notations

\mathbf{x} =decision variables representing the **sizing** and **siting**

τ =the **maintenance time** of DG system

n =number of nodes in the power system

m =number of available DG equipment type

l =number of link of the distribution network

D_j =power demand of node j , for $j=1, 2, \dots, n$

$P_j(\mathbf{x})$ =power generation at node j , for $j=1, 2, \dots, n$

$V_j(\mathbf{x})$ =voltage at node j , for $j=1, 2, \dots, n$

$I_k(\mathbf{x})$ =current in link k , for $k=1, 2, \dots, l$

P_r =rated wind turbine power output

$f_w(y)$ =wind speed distribution

S =hourly irradiance on PV, random variable

$P_s(S)$ =power output of PV

h =PV efficiency

A =PV area

T_o =PV skin temperature

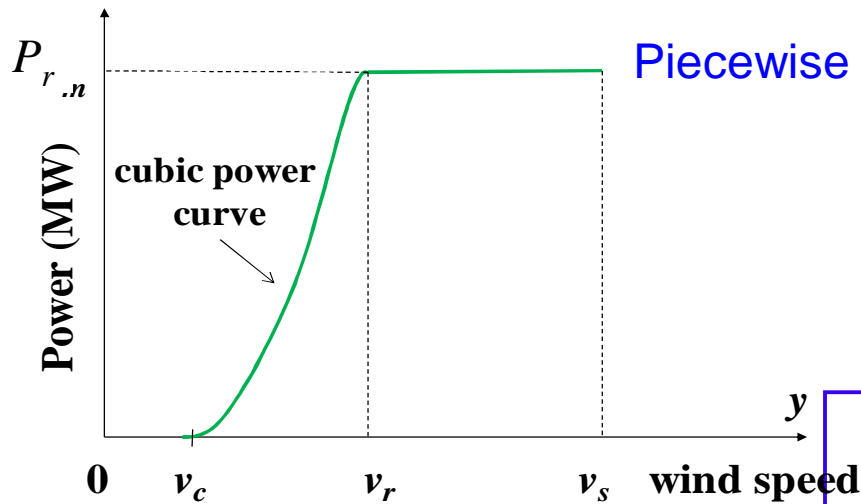
mixed integration programming problem

Modeling Variable Power Output

- Ø Time Series Model (.e.g. ARIMA Model)
- Ø DG Simulations
- Ø Astronomy/Physics Models (Observation)
- Ø Moment Methods (Mean and Variance)

The models of 'Wind' and 'Solar PV' Power generation are given:

Wind Power Generation



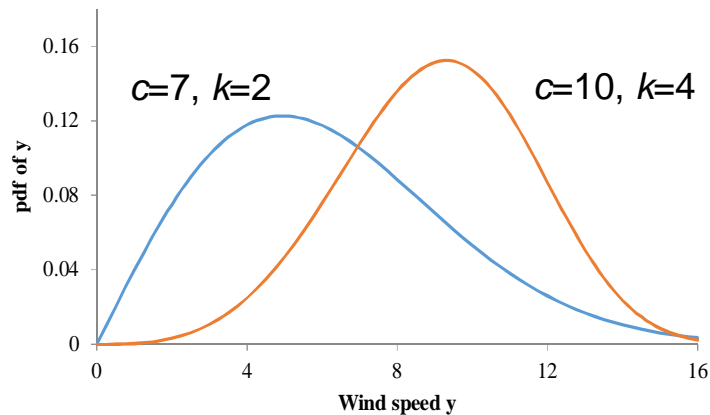
Piecewise Functions

$$P_w(y) = \begin{cases} 0 & 0 \leq y < v_c, y > v_s \\ P_r \left(\frac{y}{v_r} \right)^3 & v_c \leq y \leq v_r \\ P_r & v_r \leq y \leq v_s \end{cases}$$

density function

$$f_w(y) = \left(\frac{k}{c} \right) \left(\frac{y}{c} \right)^{k-1} e^{-(y/c)^k}$$

Weibull Wind Speed Distribution



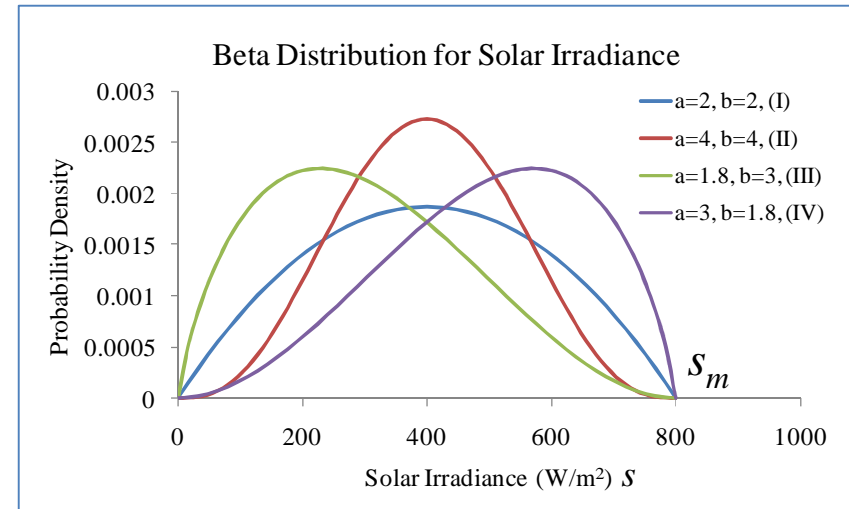
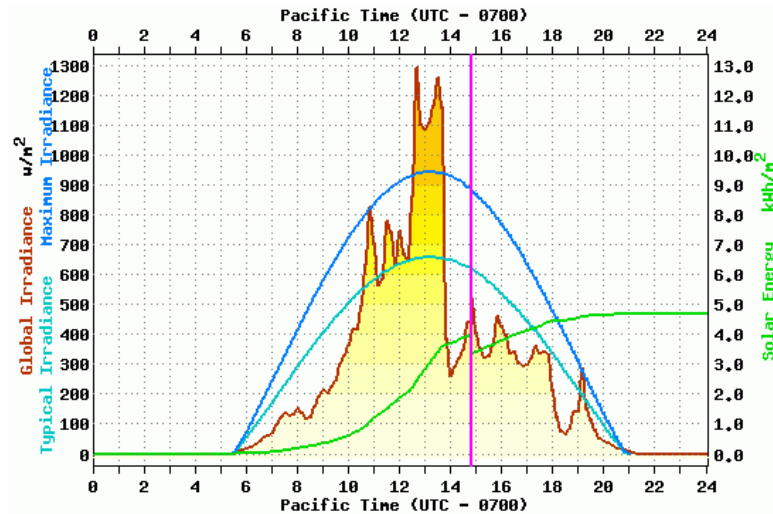
$$E[P(y)] = g \int_{v_c}^{v_r} x^3 f(y) dy + P_m (F(v_s) - F(v_r))$$

$$E[P^2(Y)] = g^2 \int_{v_c}^{v_r} x^6 f(x) dx + P_m^2 (F(v_s) - F(v_r))$$

$$Var(P(Y)) = E[P^2(Y)] - (E[P(Y)])^2$$

Where $g = P_r / v_r^3$

Solar Photovoltaics (PV) Generation



density function

$$P_s(S) = hAS(1 - 0.005(T_o - 25))$$

$$f_s(s) = \frac{\Gamma(a+b)}{s_m \Gamma(a) \Gamma(b)} \left(\frac{s}{s_m} \right)^{a-1} \left(1 - \frac{s}{s_m} \right)^{b-1}$$

Where

s_m = maximum solar irradiance (W/m²)

$P_s(S)$ = power output of PV

h = PV efficiency

A = PV area

T_o = PV panel temperature

$$E[P_s(S)] = \frac{a_s s_m h A (1 - 0.005(T_o - 25))}{a_s + b_s}$$

$$Var(P_s(S)) = \frac{a_s b_s s_m^2 h^2 A^2 (1 - 0.005(T_o - 25))^2}{(a_s + b_s)^2 (a_s + b_s + 1)}$$

Key Performance Measures of DG System

q **Technical**

- Ø Energy Supply Reliability
- Ø Power Quality (i.e. voltage stability)
- Ø Line Thermal Stress

q **Economical**

- Ø Return On Investment

q **Environmental-Social**

- Ø Carbon Savings/Climate Change

q **Political**

- Ø Renewable Portfolio Standards

Technical Constraints

Ø Reliability (loss-of-load probability):

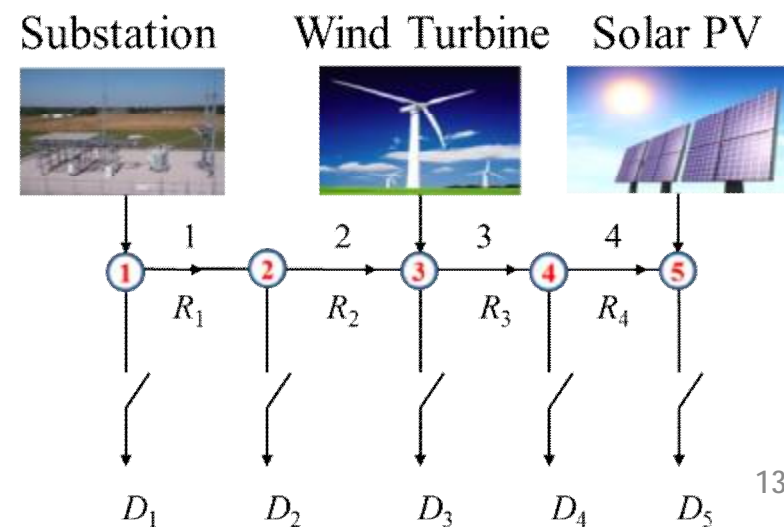
$$\Pr\{P(x) \geq D\} \geq 1 - a_1$$

Ø Power Quality:

$$\Pr\{V_{\min} \leq V(x) \leq V_{\max}\} \geq a_2$$

Ø Thermal Limits

$$\Pr\{I(x) \leq I^{\max}\} \geq a_3$$



Economic Goal

$$\mathbf{Cost} = \text{Install} + \text{Operation} + \text{Carbon Credits} + \text{Maintenance}$$

$$\Downarrow$$

$$f_1(\mathbf{x}, \tau) = C_{DG}(\mathbf{x}, \tau)$$

$$C_{DG}(\mathbf{x}, \tau) = C_e(\mathbf{x}) + C_o(\mathbf{x}) + C_c(\mathbf{x}) + C_m(\mathbf{x}, \tau)$$

$$C_e(\mathbf{x}) = \left(\frac{r(1+r)^h}{(1+r)^h - 1} \right) \sum_{i=1}^m \sum_{j=1}^n x_{ij} a_{ij} P_{ij}^c$$

$$C_c(\mathbf{x}) = \sum_{i=1}^m \sum_{j=1}^n t_i^a x_{ij} c_{ij} P_{ij}$$

$$C_o(\mathbf{x}) = \sum_{i=1}^m \sum_{j=1}^n x_{ij} b_{ij} P_{ij}^c$$

$$C_m(\mathbf{x}, \tau) = \sum_{i=1}^m \left(\frac{t_i^a (c_{fi} F_i(t_i) + c_{pi} R_i(t_i))}{\int_0^{t_i} R_i(t) dt + t_{fi} F_i(t_i) + t_{pi} R_i(t_i)} \sum_{j=1}^n x_{ij} \right)$$

Environmental and Political Goals

Ø Environmental Goal: Maximize Carbon Savings

$$\implies f_2(\mathbf{x}, \boldsymbol{\tau}) = q \sum_{i=1}^m \sum_{j=1}^n t_i^a x_{ij} A_i(t_i) P_{ij}$$

Ø Political Requirements

$$\sum_{i=1}^m x_{ij} P_{ij}^c \leq l E[D_j] \quad \text{for } j=1, 2, \dots, n$$



**Renewable
Portfolio
Standards**

A Multi-Criteria Approach to DG Planning

$$\text{Min: } f_1(\mathbf{x}, \boldsymbol{\tau}) = C_{DG}(\mathbf{x}, \boldsymbol{\tau})$$

Decision variables:
 x_{ij} (binary)
 t_i (positive)

$$\text{Max: } f_2(\mathbf{x}, \boldsymbol{\tau}) = q \sum_{i=1}^m \sum_{j=1}^n t_i^a x_{ij} A_i(t_i) P_{ij}$$

$$\text{Subject to: } \Pr\{P(\mathbf{x}) < D\} \leq a_1$$

$$\Pr\{V_{\min} \leq V_j(\mathbf{x}) \leq V_{\max}\} \geq a_2 \quad \text{for } j=1, 2, \dots, n$$

$$\Pr\{I_k < I_k^{\max}\} \geq a_3 \quad \text{for } k=1, 2, \dots, l$$

$$\sum_{i=1}^m x_{ij} P_{ij}^c \leq l E[D_j] \quad \text{for } j=1, 2, \dots, n$$

A Two-Stage Decision Making

Stage 1: Determining \mathbf{x}

$$\text{Min: } f_1^{(1)}(\mathbf{x}) = E[C_e(\mathbf{x})] + E[C_o(\mathbf{x})] + E[C_c(\mathbf{x})] + Z_{1-q} \sqrt{\text{Var}(C_{DG}(\mathbf{x}))}$$

$$\text{Max: } f_2^{(1)}(\mathbf{x}) = q \sum_{i=1}^m \sum_{j=1}^n t_i^a x_{ij} E[P_{ij}]$$

$$\text{Subject To: } m_{P(\mathbf{x})} \geq m_D + Z_{1-a_1} (s_{P(\mathbf{x})}^2 + s_D^2)^{1/2}$$

$$V_{\min} - Z_{(1-a_2)/2} s_{V_j(\mathbf{x})} \leq m_{V_j(\mathbf{x})} \leq V_{\max} + Z_{(1-a_2)/2} s_{V_j(\mathbf{x})}$$

$$m_{I_k(\mathbf{x})} \leq I_k^{\max} - Z_{a_3} s_{I_k(\mathbf{x})}$$

$$\sum_{i=1}^m x_{ij} P_{ij}^c \leq I E[D_j]$$

Stage 2: Determining \mathbf{t}

$$\text{Min: } f_1^{(2)}(\mathbf{t}; \mathbf{x}) = f_1^{(1)}(\mathbf{x}) + E[C_m(\mathbf{t}; \mathbf{x})]$$

$$\text{Max: } f_2^{(2)}(\mathbf{t}; \mathbf{x}) = q \sum_{i=1}^m \left(t_i^a A_i(t_i) \sum_{j=1}^n x_{ij} E[P_{ij}] \right)$$

$$\text{Subject To: } t_i > 0$$

Numerical Experiment: A13-Node Network

Input Data

- 1) The mean and the standard deviation of D_j
- 2) Wind speed and solar irradiance distributions
- 3) Wind turbine (WT) power curve
- 4) Costs associated with WT and PV maintenance
- 5) Lifetime distribution of WT and PV units
- 6) a_1 , α_2 , a_3 , and I

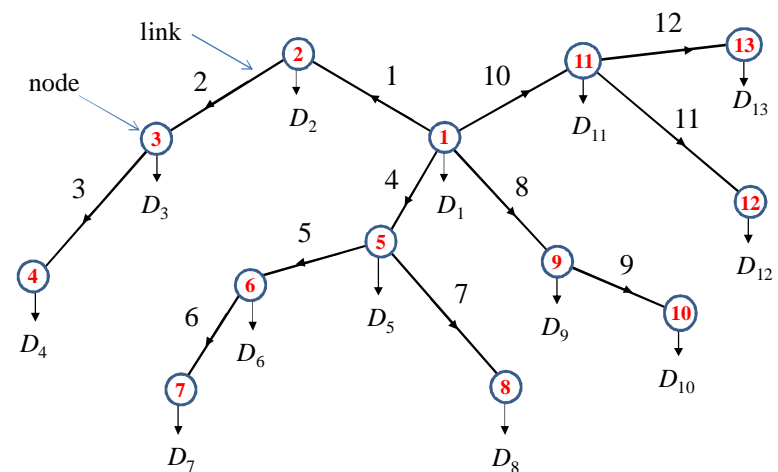
WT and PV Options ($m=5$)

i	DER	Capacity (MW)
1	WT1	1.0
2	WT2	1.5
3	WT3	2.0
4	PV1	0.5
5	PV2	1.0

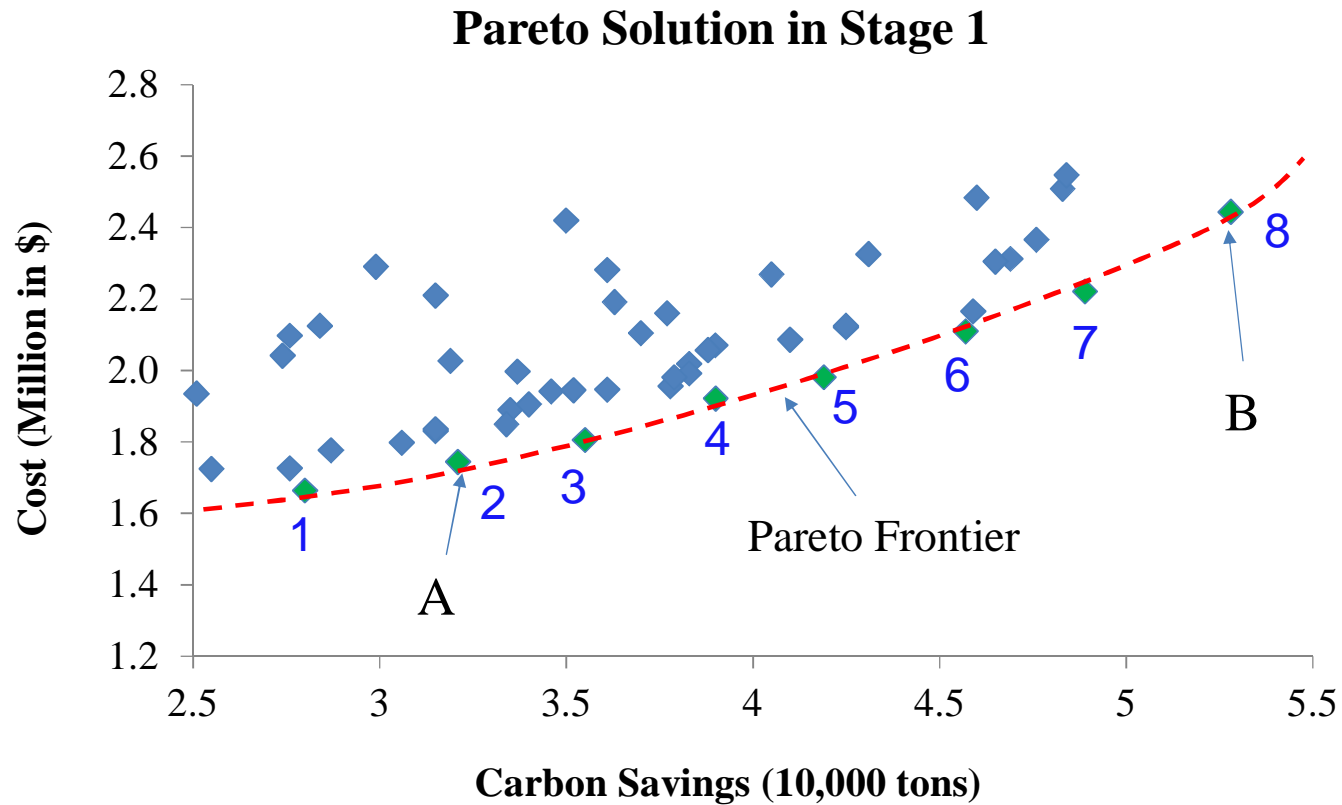
Output Data

- 1) Where to place the WT/PV?
- 2) The size of WT/PV units
- 3) The maintenance time of WT/PV
- 4) Annualized system cost
- 5) Carbon savings estimation

Testing on 13-Node Network ($n=13$)



Pareto Solution in Stage 1



Selected Pareto Solutions in Stage 2

Solution No.	1	2	3	4	5	6	7	8
Carbon (´ 10⁴ tons)	2.737	3.134	3.465	3.803	4.082	4.450	4.774	5.140
Cost (´ \$10⁶)	1.913	2.035	2.103	2.347	2.368	2.597	2.716	2.942
j=1	SS	SS	SS	SS	SS	SS	SS	SS
2	5	4	4	4	5	3	1	3
3	4	5	5	5	4	5	5	5
4	5	5	5	5	5	5	5	5
5	0	2	2	2	2	1	2	2
6	0	2	2	3	1	3	3	3
7	5	1	1	2	2	3	3	3
8	2	2	2	2	3	3	3	3
9	1	0	0	2	0	1	1	2
10	2	1	3	1	3	2	3	2
11	1	2	0	1	2	1	3	3
12	4	5	5	1	2	1	1	3
13	1	0	2	1	2	2	2	2
t₁ (hour)	2,860	2,793	2,876	2,943	2,936	3,019	3,105	n/a
t₂ (hour)	2,820	2,734	2,808	2,892	2,889	3,024	3,118	2,734
t₃ (hour)	n/a	n/a	2,869	2,925	2,957	3,041	3,195	2,773
t₄ (hour)	10,732	10,615	10,743	10,887	10,860	n/a	n/a	n/a
t₅ (hour)	7,644	7,419	7,635	7,861	7,886	8,150	8,490	7,419

(SS=Substation)

Conclusion

- q The power industry is **transitioning to distributed** and **renewable** generation to mitigate the climate change.
- q A DG planning is a **multi-criteria** decision making, taking into **4 impacts**: account economic, technical, environmental and regularly factors.
- q Propose a **two-stage optimization algorithm**: 1) **allocating** DG **siting** and **sizing**; and 2) **determining** the maintenance **times**.
- q Demonstrated on a **13-node** network, showing the benefits to reliability, voltage stability and thermal stress release.
- q Future research incorporates emerging technologies: **vehicle-to-grid** and **demand response**.



**Thank You !
Q and A**